# The Concept of Universality Class

by Paul A. Johnson, James A. Ten Cate, Eric Smith, Robert A. Guyer, and Thomas J. Shankland, EES-11 Geophysics Group

## Slow Dynamics and Universality

The concept of a universality class is the centerpiece of the modern theory of critical phenomena.*

The basic premise of present and future work is that the concept of a universality class can be applied to the description of the nonlinear elastic behavior of a broad class of materials. Our work entails extrapolating the concept of such a class from unique signatures observed in the material nonlinear elastic behavior.

Among the benefits of establishing a universal description is a vast simplification in describing materials as elastically identical over a huge number of length scales.

The materials we would admit to this elasticity universality class are remarkably disparate in their physical, meso-geometrical, and chemical makeup, e.g., granular materials, soils, rocks, some ceramics, some metals, damaged or fatigued materials, etc.

These materials owe their elastic behavior to a fabric of elastically soft features within a hard matrix ("the bond system"). The bond system exists within a small fraction of the total volume (<1%) and carries mesoscopic-to-nanoscopic-scale elastic features. These retain memory of the stress history as exhibited by slow dynamics.

Further, we hope to have the ability to use universality for nondestructive testing applications (membership in the universality class is a consequence of damage). For example, cracked and otherwise damaged materials have the slow dynamical signature in their elastic response.

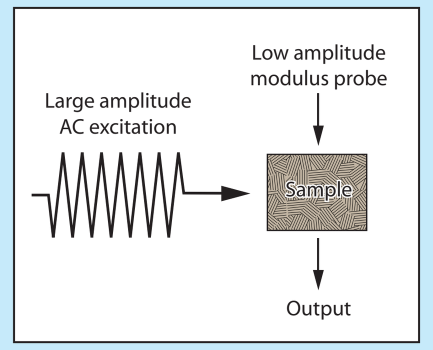
### *Interaction Range and Universality

Close to their critical point, greatly different physical systems exhibit a strong similarity. Various macroscopic properties turn out to be independent of microscopic details, but are solely determined by a small number of global parameters, such as the dimensionality of the system and the symmetry and range of the interactions between the particles. This fascinating phenomenon, universality, is explained by the renormalization-group theory, which was developed in the early seventies by Kenneth G. Wilson (Nobel Prize in Physics 1982). In the last 25 years, the universal properties of a variety of critical systems have been calculated. Many of these predictions have been verified by computer simulations, especially for so-called spin models.

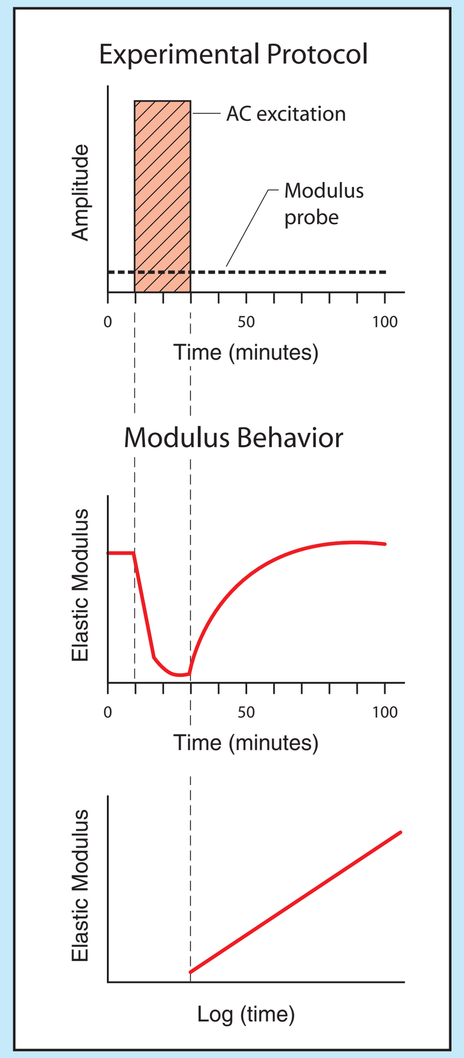
## Slow Dynamics can be understood as follows

Strike a bell, and the bell rings at its resonance modes. Strike it harder, and the bell rings at the same tones, only louder. Gently strike a bell composed of granite or sinterred metal, and it rings normally. Strike it harder, and surprisingly the tone drops in frequency ever so slightly. Strike it even harder, and the tone drops further in frequency. The frequency shift is a manifestation of a softening non-linearity resulting from the elastic properties of these and other materials. However, with the frequency shift, we observe something extraordinary: a significant and persistent alteration in the material wave amplitude, dissipa-tion and modulus, a memory of the disturbed strain state. The amplitude and modulus progressively return to their original values after hundreds of seconds, as a function of log (time).

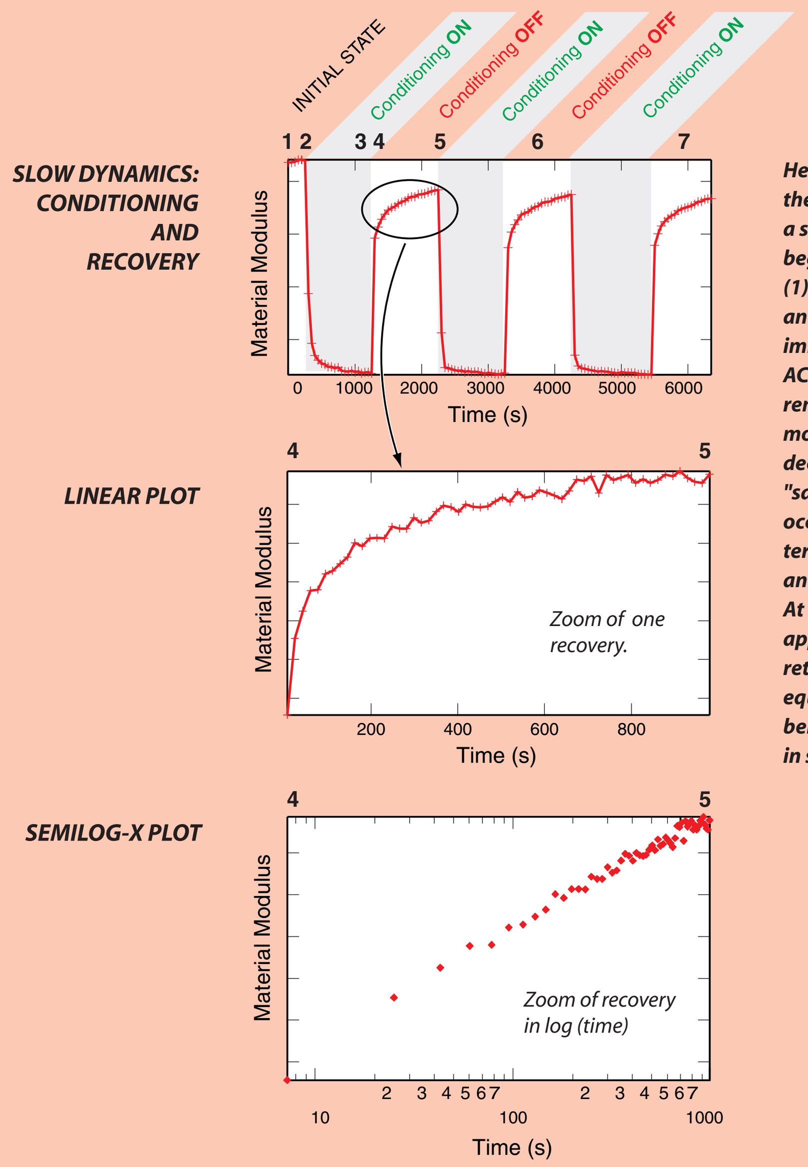
## Experiment




*A low amplitude signal ("modulus probe") continually probes the sample to record a resonance frequency. The modulus is calculated from the resonance frequency. At a certain time, a large amplitude AC signal excites the sample for several minutes. The effect of this AC signal is to decrease the modulus. After this AC signal is terminated, the modulus increases abruptly but not to its original value. From this point the modulus recovers slowly back over approximately 1000 seconds.*

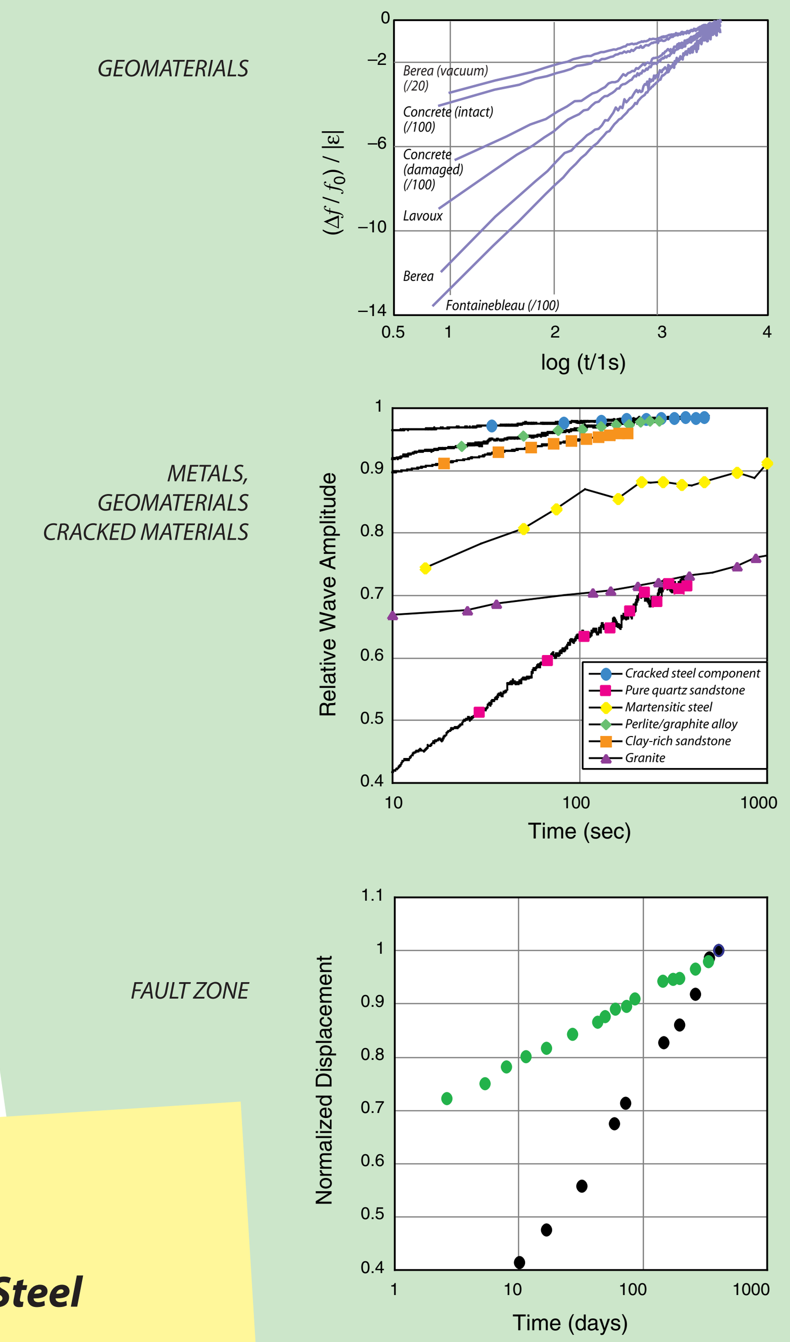



## Slow Dynamical Behavior in a Solid




*Here we illustrate a sequence of the slow dynamical behavior of a sample. The sample modulus begins at its equilibrium state (1). An AC drive is turned on, and the sample modulus immediately decreases (2). The AC drive ("conditioning") remains on and the material modulus progressively decreases until the effect "saturates" (no more decrease occurs) (3). The AC drive is then terminated ("conditioning off"), and the modulus rebounds (4). At this point the sample requires approximately 1000 seconds to return to near its original equilibrium state (5). The behavior is repeatable as seen in successive experiments (6, 7).*

## Slow Dynamics in Various Materials

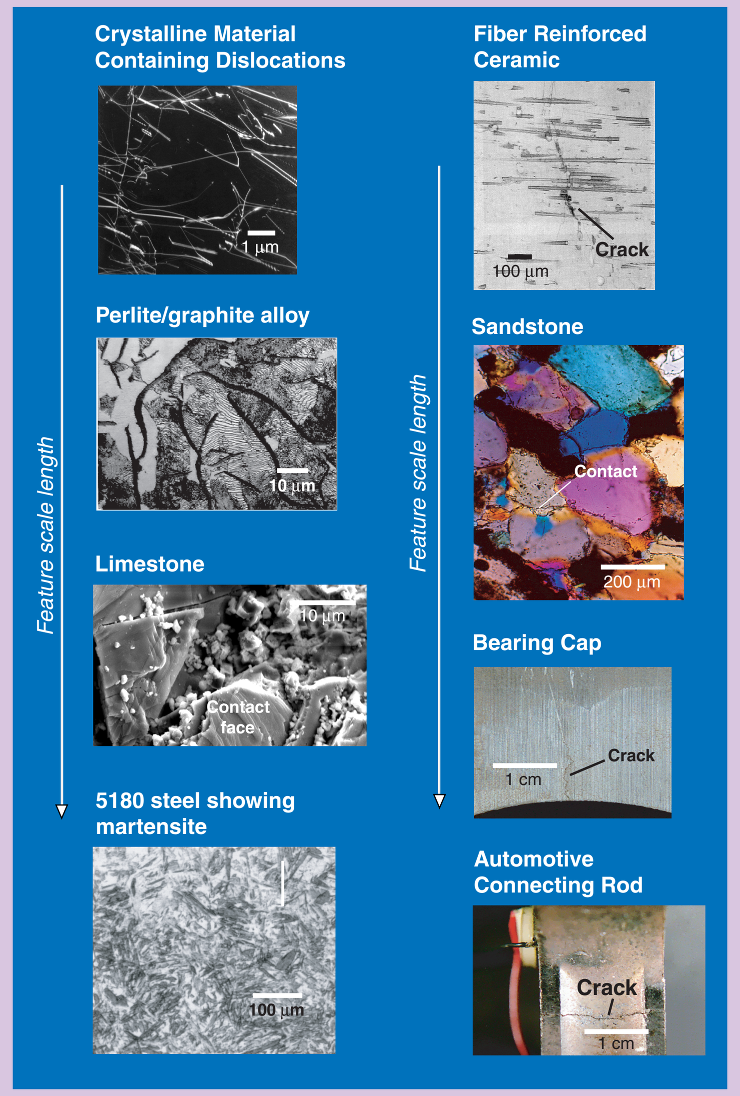



*Slow dynamics in sandstones, concrete and limestone. Here the frequency (modulus) recovery is illustrated.*

*Slow dynamics in geomaterials, metals, and cracked materials. Here the Q (inverse dissipation) is illustrated.*

*Slow dynamics after two Parkfield (1984) earthquakes. Here the normalized displacement recovery is illustrated.*

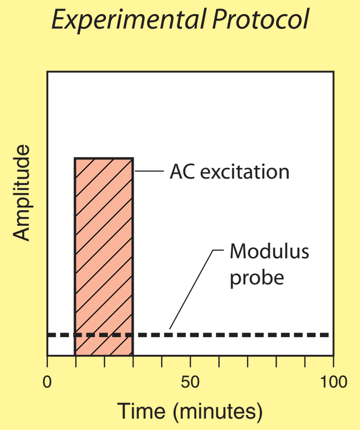
## The Increasing Scale Length of the Features Where the Slow Dynamics Originate



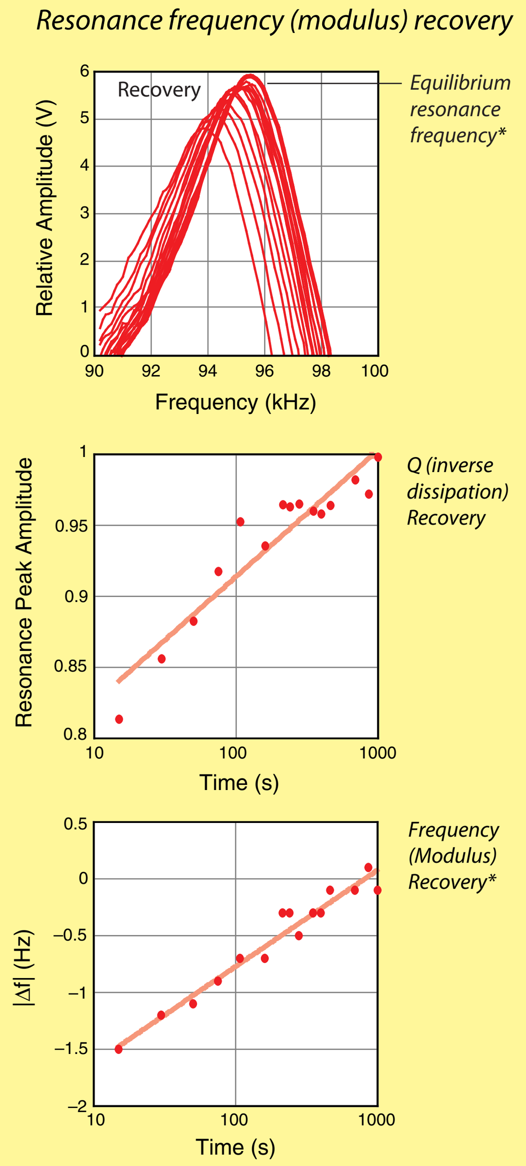

Some materials that exhibit slow dynamics

*The elasticity of nearly all materials that display slow dynamics depends on the elastically soft portions of these materials, often composing less than 1% of the material volume. It is these same features (flat pores, grain contacts, cracks, etc.) that also control access by fluids, aging, chemical reaction, etc. Understanding how the soft part of the material behaves is the key to understanding how the bulk material behaves.*

## Example: Slow Dynamics in Martensitic 5180 Steel




*Here we illustrate the slow dynamical frequency (modulus*) recovery with time. The peaks at upper right represent the resonance of an eigenmode of the steel sample. Before the large amplitude AC excitation, the eigenmode is at the equilibrium resonance frequency. Once the AC excitation begins, the resonance frequency decreases. After the AC excitation is terminated, the resonance frequency creeps progressively back to the equilibrium state ("recovery"). The recovery of the inverse dissipation and frequency are shown in the next two plots.*




*the modulus is proportional to the square root of the frequency.

## CONCLUSIONS

**Slow dynamics are destined to be a sensitive probe of the micromechanics of the system, and appear to be the primary manifestation of a new universality class. Our work is leading directly to determining long-term confidence in the safety, reliability, and performance of the Nation's nuclear weapons stockpile. The benefits to stockpile stewardship, to monitoring progressive damage in general, and to nondestructive evaluation for quality control cannot be overstated. The use of slow dynamics as a probe of nanoscale material properties will become a new domain of research.**